Coordinated Science Laboratory

UNIVERSITY OF ILLINOIS - URBANA, ILLINOIS

THREE SURVEY PAPERS:

1) A Survey of Work Done by the Bio-Systems group of the Control Systems Laboratory
2) Studies of Human Channel Capicity
3) The Informational Limitations of Decision Making

Henry Quastler

R-71 1956

This is a reprint- MARCH, 1965

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Prepared by:

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CONTROL SYSTEMS LABORATORY
UNIVERSITY OF ILLINOIS
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A SURVEY OF THE WORK DONE BY THE BIO-SYSTEMS GROUP
OF THE CONTROL SYSTEMS LABORATORY

The Bio-Systems was constituted as one of the original divisions of the Control Systems Laboratory early in 1951. It is scheduled to be disbanded in February 1956. During these five years the Bio-Systems Group has always been small but has had an ambitious and largely basic research program.

During three summers, 1951, 1952, 1953, the group was greatly reinforced by a large number of consultants staying anywhere from three days to two months. In the summer of 1954 the group arranged a one-week symposium at Allerton Park. During 1954 and 1955 the group cooperated with members of the Statistical Research Center of the University of Chicago in studying the sampling distribution of information functionals.

A - Bio-Systems

Our group first engaged in a study of living systems in which we considered them as very complex, self-checking and self-maintaining automata. The informational performance of even the most simple living system is tremendous, compared to that of the most complex existing technological information-handling devices. This performance is achieved in a poorly controlled environment under conditions technologically unacceptable for precision work. Yet, it somehow works. It is very unlikely that the performance is based on high reliability of components. Instead, it is virtually certain that living things can do what they do because of a very successful design. It was hoped that a methodological study of living things might yield some ideas of the design principles involved.

It was assumed that the modern mathematical systems theories - such as theory of information and communication, cybernetics, game theory, and others would provide appropriate concepts for such analysis.

The following documents were prepared in the course of this study:

(i) "Biological Control Systems" -- 27 essays by 25 authors collected during the summer session of 1951. This collection has been made available in multilith copies, as a report of 560 pages.

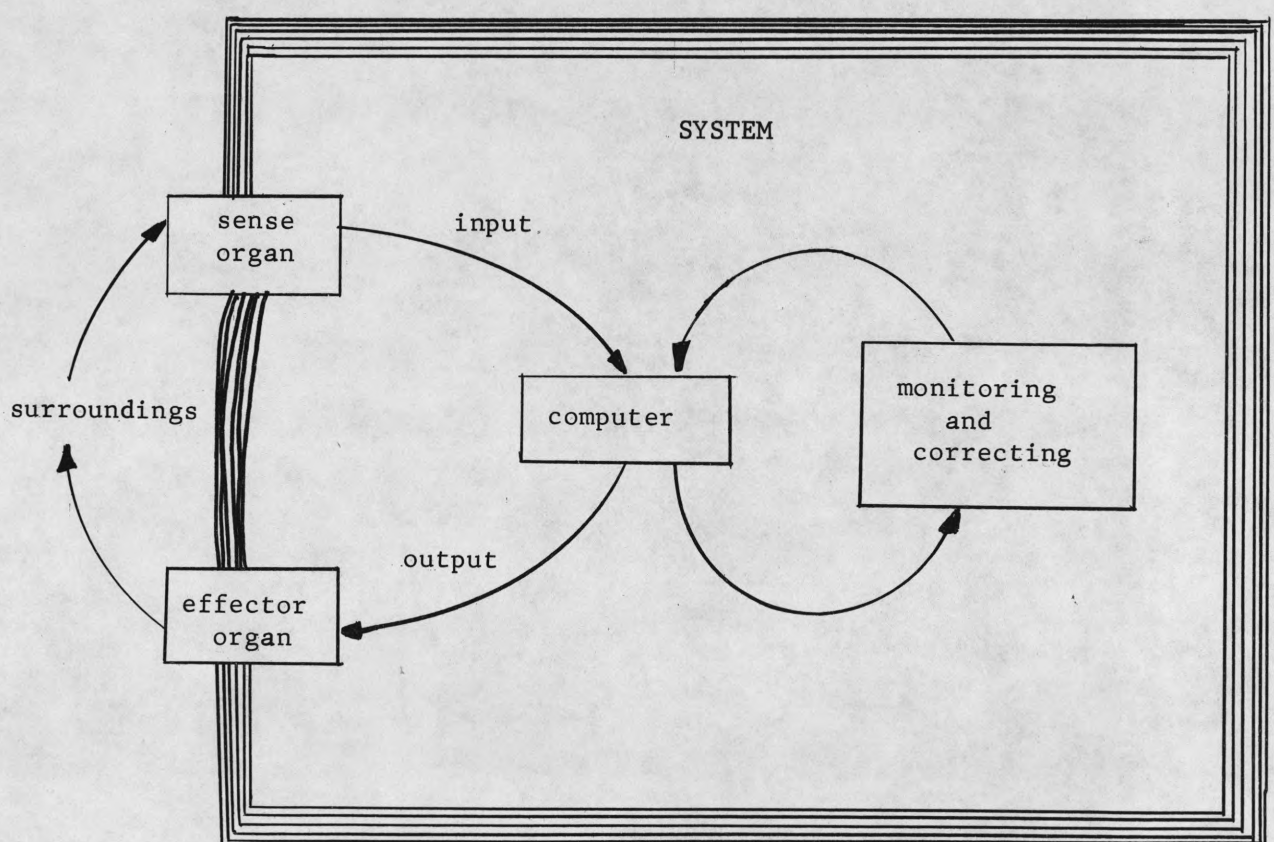
(ii) "Essays on the use of Information Theory in Biology" -- 19 essays by 15 authors, a book of 273 pages published by the University of Illinois Press in 1953. The material was largely prepared during the summer session of 1952. This volume was issued at a time when it had already been decided that the Bio-Systems Group would greatly reduce its activities in this field and it was hoped that the published account of our endeavours would arouse interest and stimulate work along the same lines at other places. This hope has been fulfilled to some degree.

(iii) "Essays on Biological Unitization" -- CSL Report R-52 (1953) of 73 pages, containing 6 papers by 6 authors. The main feature of this report is the sketching out of a new kind of analysis of biological control systems. One may expect to find material for interesting further generalization, if about a dozen more systems are analyzed in a similar fashion.

(iv) K. S. Tweedell, "Redundancy in Living Organisms: Fertility vs. Brood Care" -- CSL report R-47 (1954). A continuation of an investigation reported in the book on Information Theory in Biology.

B - Man-Machine Systems

From 1952 to 1953 the Bio-Systems Group gradually shifted from a very general consideration of information processing systems to the study of systems which are much less successful but easier to approach and of more immediate practical importance. We turned to a study of information processing by human teams. It appears that many systems of military interest will evolve into organizations of the following type:



One critical sub-system in such a system is the one labelled "monitoring and correcting". This is an activity which is expected to be under human supervision. The total flow of information through this component will be considerably greater than the capacity of a single man. Accordingly, an organization is needed; it appears to be of considerable importance to discover rational principles which can be used to design such organizations.

We have not gone far in this direction, for reasons which will be explained in the following section. The following reports, all prepared by summer consultants, deal with this phase of our activities:

(v) "A Note on the Spread of Rumor or Epidemic". J. B. Keller and J. Shmoys, 1954, CSL report R-48.

(vi) "A Note on Equations for a Class of Interaction Problems". R. Duncan Luce, 1954, CSL report R-55.

(vii) "Empirical Entropy: A Study of Information Flow in Air Traffic Control". E. L. Fritz and G. W. Grier, 1954, CSL report R-54.

(viii) "Suggestions for the Analysis of Reaction Times and Simple Choice Behavior". Lee S. Christie and R. Duncan Luce, 1954, CSL report R-53.

C - Human Information Processing

In approaching the problem of information processing by human teams, it turned out very quickly that not nearly enough was known about the properties of the basic component of such systems, namely, a single man processing information. Accordingly, the Bio-Systems Group concentrated on studies in the realm of applied psychology. They constitute the main body of work done by the group. We have attempted to obtain rational estimates of human information-processing capabilities, using the modern theoretical concepts of information theory and related specialities.

We feel that we have largely succeeded in defining human information-processing capabilities for some simple situations, and that we have outlined an approach which should work for more complex information-processing of the kind which is demanded from a man operating in a man-machine system. Some of the results which follow are also outlined in the other two papers of this report.

The following reports were prepared in the course of this activity:

(ix) "Human Performance in Information Transmission, Part I: General Remarks, Part II: Sequential Tasks". H. Quastler and V. Wulff, Feb. 1955, CSL report R-62.

(x) "Human Performance in Information Transmission, Part III: Scale Reading". J. W. Osborne, H. Quastler and K. S. Tweedell, Oct. 1955, CSL report R-68.

(xi) "Human Performance in Information Transmission, Part IV: Flash Recognition of Letters and Cards". L. Augenstine, et al., 1956, CSL report R-69.

(xii) "Human Performance in Information Transmission, Part V: The Force of Habit". B. Brabb and H. Quastler, 1956, CSL report R-70.

(xiii) "Human Performance in Information Transmission, Part VI: Evidence of Periodicity". L. Augenstine, 1956, CSL report R-75.

(xiv) A Survey Lecture on "Studies of Human Channel Capacity", given at the 3rd London Symposiums on Information Theory. It will be published in the proceeding of that symposium, and is included in this report. (R-71, 1956).

(xv) An essay on "Informational Limitations of Decision Making", a sketch of the expected manner in which our results could be applied to more complex human activities. This essay also is included in this report (R-71, 1956).

(xvi) "Information Theory in Psychology: Problems and Methods". A book of 428 pages, containing 30 articles by 23 authors, published by the Free Press, Glencoe, Illinois, (January 20, 1956). The content of this book is largely made up of the proceedings of the summer conference of 1954 at Allerton Park.

(xvii) "A Study of Human Performance in Filtering Information". The report of an experimental investigation performed in cooperation with members of the Systems Analysis Branch of the Naval Research Laboratory. This report will be issued early in 1956. H. Quastler

(xviii) A review article to be published in the Yale Scientific Review. L. Augenstine and H. Quastler.

D - Applied Mathematics

In the course of making experimental studies of human information processing it was found that existing methods of computing information measures were often not adequate for our purposes. A parallel situation was found in studying evidence of periodicity. Accordingly, the Bio-Systems Group undertook some investigations in applied mathematics.

The following documents were prepared in connection with this activity:

(xix) "Note on Information Entropy for Quantized Normal

Distribution". A. A. Blank, May 1953, CSL report R-40.

(xx) "Notes on the Estimation of Information Measures". A.A. Blank and H. Quastler, 1954, CSL report R-56. A survey of several approximation and bracketting methods to estimate information measures under favorable conditions.

(xxi) Informal notes on a Session of Information Theory which was held during a meeting of the American Institute of Mathematical Statistics in the fall of 1955 at Ann Arbor, Michigan. Three papers were given at that meeting by B. McMillan, D. Slepian, and H. David. A multilith copy of the manuscript is available; however, it does not constitute a formal report.

(xxii) "Sampling Distribution of Information Functions". This describes work done in conjunction with members of the Statistical Research Center of the University of Chicago (K. Brownlee, H. David and W. Kruskal) using the digital computer of the University of Illinois. One or two reports will be issued early in 1956 (R-76).

(xxiii) "Empirical Sampling Fluctuations of Information Measures". L. Augenstine and H. Quastler. The Sampling Distribution found empirically is roughly the same as that which would be predicted on the basis of simple multinomial sampling. This report will be issued early in 1956 (R-77).

(xxiv) "Sampling Distribution of Autocorrelation and Power Spectrum Functions". L. Augenstine. These functions were designed to detect sinusoidal-type periodicities. It was hoped

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that they could be adapted to the analysis of non-sinusoidal periodicities. Monte Carlo methods were used in a limited investigation of the dependence of the above functions on the sample size and the wave form. This report will be issued early in 1956 (R-78).

(xxv) "Elements of Applied Information Theory". H. Quastler. In connection with doing experimental research using information theory, the group acquired some experience in teaching the applications of information theory. A text book, based on this experience will be issued as a Technical Memorandum by OOR, early in 1956.

CONCLUSION

It is our feeling that the work of the Bio-Systems Group has been brought to at least partial completion. We have produced proof of feasibility that human behaviour information-processing can be subjected to rational analysis with the help of modern theoretical approaches. This result could not be used in attacking our earlier problems of information processing by human teams. Finally, we feel that we have made some progress, especially methodologically, toward our first goal, the analysis of complicated automata.

STUDIES OF HUMAN CHANNEL CAPACITY*

In this paper, we will discuss strategies of studying the factors which limit human channel capacity: sketch three typical experimental studies, give a descriptive catalog of factors known to limit human information transmission; and finally, mention possibilities of further development.

EMPIRICAL CHANNEL CAPACITY

"Channel Capacity" is a function which can be rigorously determined for well-defined channels. In dealing with man, a channel which is poorly known, poorly controlled, and has an enormous range of possible inputs and outputs, the rigorous method is not practical. So, one is reduced to a direct empirical approach. This involves a modern variant of time-motion studies with "amount of information transmitted" in the role of the commodity produced. The results of such studies will be peak rates of observed information transmission, not true channel capacities in the rigorous technical sense. Such values have the nature of records - not in the sense of outstanding individual performances, but rather referring to the experimenter's ability to find conditions under which individuals of good but not extraordinary competence can transmit information at high rates. We claim that these empirical channel capacities are the best available estimates of true channel capacities, and that they remain valid estimates until higher transmission rates are actually achieved in a reproducible fashion.

Man's capability of transmitting information is limited by what

* Lecture given at the 3rd London Conference on Information Theory, Sept. 1955. It is reproduced here with the permission of the Buttercroth Scientific Press, publishers of the complete proceedings of the conference.

inputs he can receive, what outputs he can generate, and to what degree he can lawfully associate inputs with outputs. Man is a highly non-linear channel, subject to several partly interacting limitations. We study all limitations in terms of transmission rates. This does not mean that they must have the character of a channel capacity; limiting factors of various other types have been encountered in experiments.

If we want to study ultimate limitations, we have to use situations where information transmission is at its best. It is quite obvious that in most actual situations transmission rates will be much below the highest rates obtainable. Some conditions for high transmission rates are: the stimuli must be easily perceived and discriminated, and the responses easily executed. All compatibilities must be good (not only stimulus-response compatibility, but also stimulus-stimulus and response-response compatibility[7]). The subject should be competent, and thoroughly familiar with his task; he must understand what he is to do, and be properly motivated; he must be allowed to organize his activities in the best fashion. The task chosen must be such that a large fraction of the subject's effort goes into measurable information transmission. All this makes considerable demands on the experimenter's skill and patience; most of the test performances in the standard repetoire of the psychological laboratory can not, and do not, approach peak rates. It seems that Licklider[13] was the first to study human transmission under near-optimum conditions; up to now, he has not had very many followers.

Suppose an observer has measured a certain rate of information transmission; the conditions being favorable, he may suspect that the observed performance is near optimum. In order to test it, one must first ascertain that the limitations are central and not on the input or output side. Input limitations can be excluded if it can be shown that the subject can handle more detailed inputs if the information content is reduced by using highly redundant inputs. Similarly, output limitations can be excluded if it can be shown that the output can be increased if the informational demands are reduced, for instance, by rehearsing the performance. Next, one should try to vary the informational challenge (input information) and see how the subject responds. Typically, one observes that small challenges are answered with perfect transmission; as the challenge increases progressively, errors become increasingly frequent; very heavy challenges lead to a breakdown of transmission ("confusion effect"). If the transmission rate is plotted on the same scale as the input information, then a curve results which begins as a straight line rising under a 45° angle, turns smoothly into a plateau or a flat maximum, and declines again. Only when one has observed the peak of the curve can he confidently assert that he has reached the peak value with respect to the particular mode of challenge investigated. The informational challenge can be varied in a number of ways: by varying the speed, the precision requirement, information content per single act, logon content, etc. Only when one has challenged in a variety of modes can he feel confident of having approximated the peak value for the activity studied.[1,17,20,21]

In most cases so far studied, the peak transmission rate was found to occur at a stage when the subjects made a few errors, and was only slightly larger than the transmission rate associated with the best error-free performance. However, this experience had to come out of studies in which subjects were pushed way beyond the limit of error-free performance; a similarly exhaustive study will be needed in every radically new situation. This involves the estimation of information transmission in the presence of many errors. Basically, this is no problem; but it entails considerable practical difficulties. The estimation of transmission rates depends on estimating the probabilities for all input-output combinations. In psychological experiments, there may be very many such combinations; in fact, there always are when conditions are favorable for high transmission rates. For instance, in a letter-recognition experiment, there are 26 possible inputs and as many outputs, or 676 stimulus-response pairs - not taking into account inter-symbol influences. In order to obtain a probability measure for each category, very large samples will be needed, which leads to an inordinate amount of labor in gathering and processing data. Moreover, during a long series of trials the underlying conditional probabilities will change. Thus, it is essential to develop approximating shortcuts which reduce the number of probabilities which must be estimated and, thus, the sample size[2,24]. The more such shortcuts an investigator has at his disposal, the more likely he will be to find one appropriate for a particular situation studied. Even so, sampling fluctuations of information functions present a serious problem. Miller[15] and others have given asymptotic formulae for the sampling distributions which yield good estimates of the first and second moment of the distribution even for small sample sizes. However, their performance is poor for the tails of the distributions which determine the confidence intervals, and these are what the experimenter needs. So, a team was formed consisting of 3 statisticians, 2 experimenters and one high-speed digital computer, in order to investigate complete sampling distributions with the help of Monte Carlo methods. With this procedure, particular experiments can be tested in a straightforward manner; one just explores various likely or possible probability sets, and investigates directly the associated sampling distributions. We also considered producing a table of various characteristics values, but, it turned out that this table would have to be very large. Therefore, we returned to the search for analytic approximation of the sampling distributions. As of now, the best approximation is one developed by H. T. David[6]; it is very nearly normal up to the 5% tails with samples as small as 11 or 31. The work is not finished and we hope to find still better functions.

EXAMPLES OF EXPERIMENTAL STUDIES

In the preceding section, we have stated what we consider the proper strategy for experiments on human channel capacity. We know of no group of experiments which fulfills all of our postulates, including, alas, the work done in the author's laboratory. We do have, however, several experiments which do not fall very short of our goal. Three of them will be briefly sketched here.

A - A Study of a Sequential Activity: Piano Playing

We have investigated rates of information transmitted in playing piano[21]. In order to be sure about the information input, we let the subjects sight-read "nonsense" sequences of notes, constructed with a table of random numbers. After some pilot tests, we chose as our experimental music a single-voice line, with constant rhythm, using various "alphabets" from 3 to 65 keys, each key being given equal probability*. The tests were done with three professional pianists. They were familiarized with the task; then, successive samples of about 100 notes each were presented at gradually increasing speed, coaxing the subjects into greater and greater speed until they were obviously way beyond their capabilities. In this manner, all alphabets were worked through**.

In general, subjects made very few errors up to a certain speed, the transmission rate increasing proportional to the speed. Then, the error rate increased. Soon, proportional trading of speed for precision was established so that the transmission rate remained approximately constant. At extreme speeds, the performance deteriorated rapidly ("confusion effect"). Individual differences were small.

The results can be summarized as follows (Table): the performance is limited by an effective range of about 50 keys, an effective speed of about 5.2 keys/sec, or a transmission rate of about 22 bits/sec, whichever imposes the lowest limits; if the challenge in one direction (speed or range) is very small, then the performance in the other is somewhat higher

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* Attempts to increase information transmission by utilizing additional dimensions (2 or 4 voices, added text, added chords, added rhythm) failed; they resulted in compensatory or worse than compensatory slow-down. We probably could have improved the transmission rate a little by using various intervals with unequal frequencies, according to their relative difficulty.

** In similar tests with typewriting[21], we used two alternatives methods of challenging: increasing speed with constant alphabet, and increasing alphabet sizes at constant speed. The results were the same.

than in the neighborhood of the peak transmission rate ("simple challenge effect"); if the challenge is extremely high, then transmission rate drops below the optimum ("confusion effect"). It is important to note that the limitations of information transmission differ, depending on the conditions used; hence, studies performed in different restricted domains would have yielded apparent contradictions.

Table: Piano Tests
(average values)

Size of Alphabet*	Highest Effective Speed** (keys/sec)	Transmission rate (bits/sec)	Remarks
3	6.5	10	Simple Challenge Effect
4		13	
5	5.2	10	Speed Limitation
9		16	
15		19	
25	4.9	23	Channel Capacity
37	4.4	22	
65	2.8	17	Range Limitation

* Number of keys used; repetitions being excluded, the number of equiprobable alternatives is one less than this number.

** The no. of keys per second which, if executed flawlessly, would yield the peak transmission rate.

B - <u>A Study of a Single-Act Performance: Scale Reading</u>

We repeated and generalized Garner and Hake's classical experiment[8] on how much information can be acquired, in a single glance, about the position of a pointer on a scale. We modified their arrangement by using a strip of squares instead of a scale, and a brightly colored marker instead of a pointer[17]. Furthermore, we gave the subject redundant information by coloring every other square, and by using different colors for whole regions of white and colored squares. So assisted, subjects can assimilate 4.3 bits of information at a glance, i.e., they effectively discriminate about 20 squares in a strip. This rate is reached with strips of 24 squares.

Next, we displayed simultaneously two strips of 24 squares, with one marker on each; this yielded 5.2 bits of information. Three strips and 3 markers gave only 5.6 bits. This low value suggested that the number of squares which is optimum for a single strip is not the best for multiple strips (due to the confusion effect). This was confirmed in a comprehensive study in which we used from 3 to 24 squares per strip, and raised the number of strips in each case beyond the saturation point (using up to 12 strips). With fewer squares per strips, subjects can easily transmit 7 1/2 bits from 3 scales. The limitations found were: subjects can assimilate the equivalent of up to 5 1/2 squares per strip, and the equivalent of up to 5 1/2 strips perfectly discriminated. There is no limitation which has the character of a channel capacity*: the limiting factors are logon content[14] (number of strips) and span of absolute judgment[8,16] conjunctively[4], i.e., whichever imposes the lower limit is effective. These limitations are valid in the neighborhood of optimum performance; there is a simple-challenge effect if only one or two strips are used; we presume that a similar effect would be obtained by minimizing the challenge in the other mode, using only 2 squares per strip.

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* The total amount of information assimilated in this experiment is not a maximum for a single-glance performance; higher values have been obtained with letters, playing cards, and combinations of letters and dials.

C - A Comparative Study of Disjunctive Reaction and Sequential Activity: Typewriting.

Several researchers[3,5,9,10] have studied disjunctive reactions, and obtained transmission rates by comparing disjunctive reaction times for disjunctions of different informational values. Typically, rates of about 10 bits/sec were found*.

We made an experiment on disjunctive reaction times with the typewriter. Subjects had to type 1, 2, or 4 letters.[22] Thus, this study provided a bridge from single disjunctive reaction to the sequential activity previously studied[21].

Two subjects took an average of .24 sec to respond if they knew which letter was coming**. Typing a single unknown letter, selected at random from the whole alphabet, took .53 sec; differences between letters were related to the position of the letter on the keyboard, but not to frequency of occurrence in English tests. With a set of 4 easy letters, the reaction time was less (.45 sec). However, when we used different tetrads of letters, and compared the reaction times with those found when the same letters occurred in a 26-letter experiment, we found that the gain in reaction time was only 3 - 9%. For alphabets of 8 and 16 letters, the gain was negligible. On the other hand, increasing the alphabet to include numbers and symbols would result in much slower average reaction times. Thus, the limiting factors are range and speed, and not channel capacity.

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* With one exception, where the rate was 22 bits/sec.[12]

** A third one took .14 sec, but she seemed not to wait until the letter was visible.

Experiments with 2 and 4 unknown random letters (from the whole alphabet) produced a simple result:

$$t_n = 0.240 + 0.285n$$

where

n . . number of unknown letters

t_n. . time from onset of display to execution of n'th letter (in seconds)

There are deviations from this rule which are statistically significant but small compared to the main effect.

Subjects make very few errors in this test. We credit them with 4.5 bits per letter, and obtain an information flow of 4.5/0.285 = 16 bits/sec. This is considerably more than the values obtained in most tests of disjunctive reaction times. By manipulating the input probabilities we should be able to raise the transmission rate still a little higher.

The same Ss were asked to copy sequences of 200 random letters at high speed. In this test, they used about .30 sec per letter, or very slightly more than in the tests with 1-4 letters*. Why this constancy of time? We surmise that it is due to habit. A typist entering the profession is supposed to write about 50 words per minute, which means about 270 msec per letter. This is her habitual speed and she will not utilize restrictions of the alphabet or of the length of the text to increase it.

This study shows up two effects of habit: high rate of information transmission and inflexibility of the activity pattern.

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* The error rate was fairly high; T-values were from 10-16 bits/sec. In earlier tests, where other subjects went through long practice sessions with long random sequences, we reached about 16 bits/sec.

FACTORS LIMITING HUMAN INFORMATION TRANSMISSION

The following is a brief descriptive catalog of factors which have been found to limit human capabilities of transmitting information. The list of categories is probably not comprehensive; neither is it orthogonal; it is nothing but a digest of experience up to this date.

a. Span for Simultaneous Activities

Man can attend to several activities simultaneously; it seems to be easier to do a little about several things than to do very much about a single one. But, when a single activity involves information processing at a high rate, then it effectively blocks other informational activities; witness the distracted professor. As far as we know, the only successful combination of activities was achieved by Licklider:[13] people can read incoherent words at about 25 bits/sec, and point at successive targets at about 15 bits/sec; if words are written across the targets, then the two activities can be performed at an almost additive rate of about 35 bits/sec.

The restriction on simultaneous activities applies to conscious information processing only; it does not apply to the total interaction of an organism with his surroundings, still less to the totality of all information-processing in a living organism.

b. Speed

We view information processing as a sequence of discrete decision processes; the unit acts can be performed effectively only up to a certain limiting speed. This speed is independent of the information content per act, within certain limits imposed by limited channel capacity on one hand, by the simple challenge effect on the other.

c. Logon Content

Tasks involving the same amount of information transmission can be set up in different ways, with results which are not psychologically equivalent. For instance, the task of locating a dot on a scale with 64 intervals is informationally equivalent to that of locating the dot on a 8 x 8 checkerboard. Psychologically, the two tasks are of very different difficulty; the two-dimensional task is much easier.

We adopt MacKay's[14] term "logon content" to describe the number of different kinds of information contained in a unit*. It is important to realize that number and kind of logons are not properties of a given situation but functions which depend on the mode of representing it. Thus, in psychological recognition tests, the logons used by the experimenter to construct a display are not necessarily those which the subject uses for recognition. So, we do not have reliable estimates of the human logon capacity[11,17,18].

The limitation on logon content for simultaneous display is called, with George A. Miller[16], the "span of perceptual dimensionality"; for presentation sequential in time, the "span of immediate memory". Both spans include usually about 7 logons.

d. Amount of Information per Logon

The informational capacity per logon per unit act is called the "span of absolute judgment"[8]. It ranges from 2.3 to 3.2 bits. Spans of double size are found in some cases.

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* Other terms used; order of complexity, numerosity, dimensionality, number of elements, of aspects, of attributes, of degrees of freedom.

One gets different limiting values (or spans) depending on whether most of the challenge is in a single mode, or in two modes simultaneously. Thus far, no experiments have been done (as far as we know) where the subjects were challenged in three or more modes simultaneously. We suspect that further lowering of the limiting values would result.

e. Filtering and Organization of Information Processing

If the informational challenge crowds or overtaxes a man's information-handling capabilities, then it might be appropriate to improve the situation by re-organization. For instance, if the difficulty is one of speed, then it might be possible to so recode the information as to produce fewer chunks of greater information content. When recoding promises no help, then one might select pieces of information according to their value. These activities involve information-processing. If they must be done at a time of informational stress, then they cannot be very effective. Faced with two strong a flow of information, man can filter and recode up to a certain degree; soon he switches to random sampling of information, and from there to complete confusion is but one step.

f. Channel Capacity

With piano playing, we found a limiting transmission rate of about 22 bits/sec. For reading, Licklider[13] found a peak rate of about 25 bits/sec* with random sequences of words; for coherent English text, we found about 24 bits/sec[21]. Data on "lightning calculators", under some plausible assumptions on their mode of procedure, indicate that

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* Richards and Swaffield[23] mention a higher value, but only as an upper bound.

they process information at 24 bits/sec[21]. Informal estimates of the rate of information transmitted by a good proof reader, and by a good tennis player, gave the same result, about 25 bits/sec[25]. We are inclined to believe that we are dealing with an <u>invariant</u>, characteristic of single over-learned activities, near-optimum conditions, and performance times of the order of minutes or seconds.

There are a number of experiments in the literature where transmission rates were measured under obviously sub-optimal conditions, and rates of much less than 20 bits were observed. This needs no explanation.

OUTLOOK

The methodology of the study of human channel capacity contains elements of the methodologies of time-motion studies, of psycho-physics, and of communication theory. Its specific traits are due to 5 effects:

(i) The non-stationarity of human behavior: this makes it necessary to use small samples, to short-cut methods, and to investigate confidence intervals;

(ii) Multiplicity of limiting factors: the informational capacity may be limited by one or more of several factors. In general, optimum performance occurs when there is a balanced challenge in several modes (such as speed, logon content, information per logon, etc). This effect calls for the investigation of a wide variety of conditions.

(iii) The simple challenge effect: the performance with respect to one particular factor is best if the informational challenge in the other factors is minimized; however, the total transmission is not as good as with a balanced challenge. Experiments in psychological laboratories tend to be of the simple-challenge type, and their results are not indicative of the behavior at optimum transmission.

(iv) The confusion effect: it prevents measuring informational capabilities simply by using very large amounts of input information; one has to investigate a large range of informational challenges to find the peak transmission value;

(v) The force of habit: it causes high transmission values and low flexibility. Because of the first effect, one will do well to study well-habituated activities; because of the second, one must adjust his experiments to the habitual pattern if he wants to avoid spurious results.

With proper methods one can measure amounts of information processed in many simple tasks, ranging from laboratory experiments to every-day activities. What benefits can be expected from such measurements? The application to human engineering is obvious, particularly if it should turn out that human information transmitting can be described by a limited number of invariants.

The following values begin to look like invariants:

(i) Maximum amount of information of a single kind, in a single chunk - about 2 1/2 bits (about 1 bit more if there is no other informational challenge; about 5 bits in particular highly skilled performances).

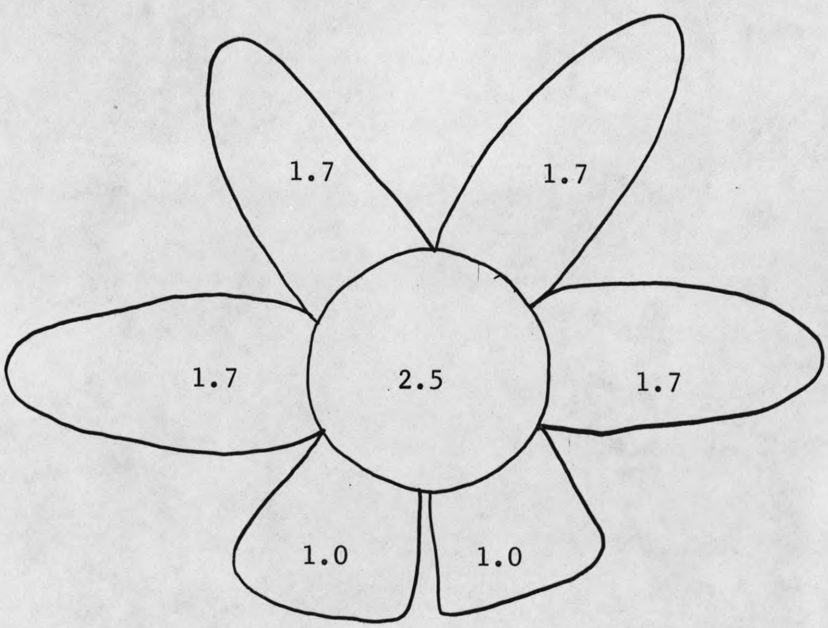
(ii) Maximum amount of information of all kinds in a single unit or "chunk", (e.g., assimilated in a glance) - about 20 bits.

(iii) Highest transmission rate for single activities, sustained for periods of the order of minutes, without interruption - about 25 bits/sec.

(iv) Admissible number of logons in a unit - about 7.

In some cases it is possible to give detailed specifications of components of an "equivalent information network" which reproduce certain aspects of human behavior. For instance, the detailed results of the scale-reading experiments outlined above suggest the following model:

> "The limiting component is a temporary storage device which accepts information from the retina at a very high rate, and can be read out about every .15 sec. It has one storage compartment for general use, with an information capacity of 2.5 bits and 6 compartments for storage of information associated with single logons (or sub-units) of these, 4 have a capacity of 1.7 bits and 2 of 1.0 bit each. (Number and information capacities of the compartments are preliminary estimates) The single-logon compartments are filled in order to preference, with excess information spilling into the common compartment; all information components compete equally for the common compartment."



The Perceptual Daisy

This model makes detailed predictions of information transmission in scale reading: the total transmission should be 4.2 bits for 1 scale, 5.9 bits for 2, 7.6 bits for 3 and 9.3 bits for 4 scales, equally divided (which makes the bits per scale decrease from 4.2 to 3.0 to 2.5 to 2.3). If two more scales are added, they should transmit together 2.8 bits, but the transmission for each of the other 4 scales should be reduced by .2 bits, due to competition for the "general" compartment; thus the total transmission increases by only 2.0 bits. Another two scales should transmit .6 bits, but these will all come out of the other scales, so that the total transmission remains the same. The experimental results conform in great detail with these numbers. Furthermore, the model can be adjusted to the results of a large experiment in letter recognition simply by multiplying all information capacities by the factor 1.67. With a minor additional adjustment, it predicts the results of extensive experiments with playing card recognition[1]. So, the "perceptual-daisy" is entitled to be taken seriously.

Models and invariants belong in pure psychology. It seems that not only the general concepts of information theory, but also the actual results of information measurements have their place both in pure and in applied psychology. One restriction must be kept in mind: information measurements are taken at the input and output terminals of a "black box" - no matter whether these boundaries are at the skin or at the interphase between electrodes and tissue, deep inside the nervous system. By their very nature, information measurements are not concerned with mechanisms of information-processing, but with the results of such mechanisms. Their function is to establish conditions with which hypothetical mechanisms must conform.

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Postscript: All experimental studies agree that man can transmit less than 50 bits per second and assimilate less than 25 bits per glance. These numbers appear very low to many people. Some people point to the fact that a telephone channel has to carry about 2000 bits per second, and a television channel has to have a much higher capacity, in order to be considered acceptable; others point out that in visual observation or even in just casual looking we seem to be aware of many more details than can be represented in 25 bits of information per glance.

The first argument is easily disposed of. Tele-communication channels are not built for use by a single person but have to satisfy simultaneously the requirements of many persons who direct attention to different parts of the transmitted information. Furthermore, the encoding and decoding procedures are clearly not maximally efficient as far as human information transmitting is concerned. If we knew more about the mechanisms by which man acquires information and if we were willing to establish very complex encoding and decoding devices, then we should be able to reduce the bandwidths of tele-communication equipment very considerably.

It is more difficult to dispose of the second argument, the appeal to daily experience of gathering enormous amounts of information through the eyes and ears. If this experience is real then we will have to conclude that our experimental methods simply do not grasp the full range of human information processing power. This is a possibility; we prefer to accept the alternative hypothesis, that the activities which have been tested experimentally are not far from optimum, and that the personal experience of gathering large amounts of information is a spurious one.

This could be tested; one way of doing it, for instance, would be to present to observers complicated visual displays (not symbolic displays but pictures of actual landscapes with objects in them), and test the ability of observers to find certain details and see how much "noise" can be introduced without their noticing it. This test has not been made, but I expect that it would reveal that a large amount of changes can be introduced unnoticed by an observer. Against the daily experience of our finding a small object in a complex display, we would like to place the equally frequent experience of our not seeing something which is right in front of us if it is not in the place where we expect it to be.

We claim that man's subjective experience of his own information-processing is coded in such a way as to lead to a vast overestimate of the amounts of information actually processed. But what we actually see is a very rough picture with a few spots in clear detail. What we <u>feel</u> we see is a large picture which is everywhere as clear in detail as the one favorite spot on which we concentrate our attention. Roughly speaking, the area of clear perception includes less than 1% of the total visual field and carries probably more than half of the total amount of information assimilated in a glance. If information assimilation would be equally successful over the whole visual field, then of course the total amount of information assimilated would go up by two or three orders of magnitude. I do not believe this to be the case.

THE INFORMATIONAL LIMITATIONS OF DECISION MAKING

For the last three years, my associates and I have been busy studying the channel capacity of human beings. That is, we have tried to learn how many bits per second can be squeezed through a man under optimum conditions. One of these conditions is that transmitting information take the form of simple activities such as copying random sequences of letters, recognizing positions of pointers on dials, etc. This is a fascinating occupation, but we did not pursue it for its own sake. We were committed to do systems research, and from this point of view it is sufficient to know that human channel capacity is pathetically small, and that one should never use man in doing a mechanical job of transmitting information unless a better transducer is absolutely not available. In this sense, it is hardly necessary to have precise information on just exactly how low man's channel capacity is, and what factors make it so low. But, there is a reason why detailed studies of the informational capabilities of man can be of great importance to system research. The reason is that these limitation are operative in the performance which is most eminently man's special function in all large systems, namely, the making of decisions.

Making of Decision and Transmitting of Information

It is not immediately obvious that the making of decision and the transmitting of information are one and the same activity. That they are, will become clear if we analyze the process into its components. In the decision process, a situation is registered; it is evaluated according to some sets of principles; as a result of the evaluation, an action is selected and executed. Random elements may affect each and every one of the three basic components: the gathering of information, the evaluation of the situation, and the selection and execution of an action. In transmitting information, an input is recorded; a code book is consulted; as a result, an output is selected and executed. Again, all three phases of the process are subject to random processes, called "noise".

The fact that decision-making and information-transmitting are studied by separate people in separate laboratories is just a consequence of emphasizing different aspects of the same process. Students of decision-making are interested in the rules which are used to select a given action in response to a given situation. The study may be a normative one, the problem being which outputs to choose if inputs and values are given. In other cases, the study is inductive, departing from inputs and outputs and trying to establish the system of values. Both studies are concerned with the <u>motivational</u> aspect of decision processes. Great care is taken not to have the process disturbed by informational limitations; one usually attempts to represent the situation with lucidity, to give the subject ample time and facilities to arrive at his decision, and to arrange a simple set of actions from which to select; in fact, in a large number of studies the range of possible actions is reduced to two. If one studies the <u>informational</u> aspect of decision processes, then one takes equally good care that there should be no doubt about what rules ought to be applied, and no difficulty in actually applying them; inputs and outputs are selected so as to give maximum transmission rates and this, in man, means always a choice between more than two alternatives.

There are good reasons why the motivational and informational aspects of decision processes are studied separately; but, it will be profitable for both groups of students to establish a solid connection before they drift too far apart. Most actual instances of making decisions and transmitting information are bound to lie between the two extremes preferred for laboratory investigations. As a rule, input information is presented in a large variety of modes, and with very different degrees of lucidity. The choice of an output can be highly specific or vague, it can be final or subject to modifications. The decision rules to be used can be selected from a large variety of possible strategies; there are few cases where a man will be absolutely certain which strategy to choose, and still fewer in which he has both the time and the skill to search for the optimum strategy. A man weaving his way through traffic on a busy road bases his decisions on as much information as he can gather and evaluate in the limited time available. His behavior will be between that of a laboratory subject in an experiment on decision making, and that of a laboratory subject in an experiment on information transmission. The typical situation of a man in a large man-machine system is analogous to that of a driver in heavy traffic; it is this kind of behaviour which we should want to know about, rather than the simplified types of behaviour which lend themselves best to study in the laboratory.

Situation, Decision-maker and Choice

The outcome of a decision process depends on the situation which calls for a decision and on the individuality of the decision-maker.

Let us consider a set of decision-makers, a set of situations with which they may be faced, and a set of possible actions from which they may select. All selection processes will be broken up into atomic units. These units can be divided into five classes by the standard procedure of multi-variate analysis:

(i) selections which are characteristic of a particular situation - that is, selections which, given the situation, would have been made by all decision-makers,

(ii) selections which are characteristic of a particular decision-maker - actions which he may take regardless of the situation,

(iii) the region of overlapping of the first two classes - such selections which any decision-makers would make in the particular situation, and the particular decision-maker in any situation,

(iv) selections which are characteristic of a particular decision-maker in a particular situation,

(v) "spontaneous" selections, made for no recognizable reason, and considered as resulting from a random process (this may mean that the selection is truly unpredictable, or that a prediction is not made because of lack of knowledge or lack of interest).

The 5 classes of selections are graphically represented in Fig. 1. The line <u>x</u> represents the set of all situations under consideration, <u>y</u> the set of decision-makers, and <u>z</u> the repertoire of possible decisions; dots and arrows which connect them represent particular unit processes:

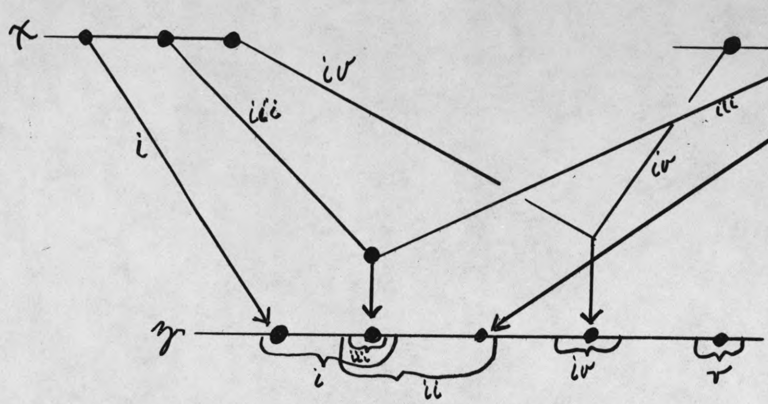

Fig. 1 Multivariate Analysis of Decision Processes

Decision processes are part of the activity in which a system copes with its surroundings. The value of each decision to the system can be assessed in terms of how far it helps it to interact with the surrounding. It is possible that a particular random choice (class v) is so lucky that it makes the system highly successful, but this is not very likely; it will be very unlikely if the system and its tasks are very complex. Also, it is quite possible that a particular decision-maker is so brilliant that his selections are favorable even if they are done without taking account of the situation present (class ii minus class iii) but this is not very probable either - again, the less so the greater the variety of tasks which the system has to perform. The valuable decisions are bound to be those in classes i and iii (depending on the situation alone) and iv (due to a complementary effect of situations and decision maker). In other words, the valuable decisions are bound to be those in which the selection contains some information about the situation which has evoked the decision process.

We may replace the unit selections by an equivalent set of binary choices between equiprobable possibilities. This substitution yields automatically the informational analysis of a decision process. Let x, the input, y, the decision-maker, and z, the output, be nodes in a tri-variate information network, and $H(x)$, $H(y)$, and $H(z)$ the uncertainties associated with these three variables. Then, the amount of information transfer associated with selections in the first class (selections predictable on the basis of the input alone) is $T(x;z)$, the information transmission between input and output. The selections of the second class produce an information transmission between decision-makers and output of the amount $T(y;z)$. Class iii represents redundant, and class iv complementary informational relations in the system; the two can not be separated; their difference is the trivariate function

$$A(x;y;z) \equiv T(x,y;z) - T(x;z) - T(y;z).$$

Finally, the informational value of spontaneous selections is $H_{xy}(z)$, or the conditional uncertainty of the choice if both situation and decision-maker are known.

It is seen that there exists no information function which corresponds to the aggregate of the three "useful" categories i, iii and iv. One restriction can remedy this situation: the personal idiosyncrasies of a particular decision-maker faced with a particular situation (class iv) may be of importance, but a large system does not have very much tolerance for individual differences. In this case, we are left with classes i and iii; this means that we have a situation where the informational value of useful decisions will be equal to $T(x;z)$ - that is, the information transmitted by all those decision processes which arrive at a selection in response to the situation in a manner not dependent on the particular decision-maker.

the system; a new proposition is substituted for the previous one that there might be a hostile aircraft. This "newness" is one of three kinds:

(i) the situation might be such that the recipient of the message knew that the statement was inevitable - in which case his amount of information has not been changed;

(ii) a particular recipient of the message did not have all the information needed to predict the decision, but this information existed elsewhere in the system; in this case, the message contains no information which is new to the system as a whole, but gives new information to some particular recipient;

(iii) something about the message (its content or its timing) could not have been predicted anywhere in the system, in which case truly new information has been generated. It is important to realize that this new information comes from the officer, not from the target. On the other hand, information concerning the target has been destroyed, namely, the possibilities that it might be a friend or an innocent bystander.

Another example: a base is attacked by a large number of enemies, more than it can defend against simultaneously. The evaluation officer has the task of selecting those enemies which represent the most immediate threats and should be dealt with first. There are very many factors which go into threat evaluation. In the face of a manifold attack, it is likely that the evaluation officer will not have all these factors available to make his decision; even if he had them, he will hardly have the time to properly weigh them against each other. In this dilemma, he might decide to select a simple rule such as: "The most urgent threat is that enemy which approaches fastest". Accordingly, he will request estimates of the radial velocities of all enemies, find them greatest in, say, targets no. 5 and 17, and come up with the statement: "Targets number 5 and 17 are the most immediate threats". This is new information; in fact, his selection might not have been quite predictable by an observer who had complete knowledge of the outside situation. Another officer, or even the same officer at some time, might have adopted slightly different rules of threat evaluation. Furthermore, the rules may not have been applied perfectly; mis-information or mis-calculation might have lead to a selection of two targets which are not actually those with the highest radical velocities. Thus, the whole system may have acquired some information which did not exist before - but it is precisely the "<u>new</u>" fraction of information which is not coherent with objective properties of the targets. On the other hand, the system probably has lost some information in the course of decision process. It is not unlikely that information was available which could or should have modified the threat evaluation; this information will not be utilized after the evaluation has been made, and is therefore obsolete and dead.

These two examples illustrate the general situation: each decision-making center gathers information from outside sources, in the form of situations reports, and from inside sources, in the form of decision rules, operating procedures, hunches, etc. On the basis of this information, an action is generated. This action usually contains <u>new</u> information. It may be locally new or wholly new. In the latter case, the "new" fraction of information is not related to the input and, therefore, likely to be of little value to the system. On the other hand, the information which has gone into the decision process has become largely obsolete and useless. Some of it might be needed for use in a subsequent decision process, but even then, it will often be easier to gather new information than to resurrect old data.

Complex Decision Systems

As a rule, important decisions concerning large systems are arrived at after a long sequence of intermediate decisions. Many decision processes yield as outputs not actions but inputs to subsequent decision processes; and, higher decisions use as inputs not direct data but the outputs of earlier decision processes. This has two disadvantages. One is a loss of informational efficiency. The over-all performance of a system is represented only by that information which flows all the way through from the input to the output side. Information transmission between elements on the same level will be necessary to coordinate their decisions; information feedback from higher to lower levels will be needed for the same purpose. However, those chunks of information are utilized and die within the system; they do not appear in the over-all effect. The more complex the organization and the more internal traffic of information is needed, the less will be the utilization of the informational capacity of the system components. Furthermore, the decision process is inherently "noisy". Each intermediate decision is liable to obliterate some input information and keep it from ever going into the final decision process. Even if each intermediate decision-maker is working according to well-established rules and doing his work efficiently and with a minimum of errors, his judgment is still restricted by the fact that his knowledge is localized; what appears to him irrelevent may be extremely important from a wider point of view. The longer the chain of intermediate decisions, the more complex the interplay of decision centers which finally lead up to the over-all decision, the greater the chance that relevant information will be lost and that the final decisions will depend much more on the properties of the system itself than on the requirements. In informational terms, a sequence of intermediate decisions is a string of noisy channels coupled in series; in such a situation, little information is transmitted, and the final output has little to do with the initial input. This is not necessarily bad; a system might be so good that it performs well regardless of the outside situation - but for this the system must be extremely good or extremely lucky.

From these considerations one will deduct the postulate that one should postpone all decision-making until the need for a decision becomes imperative. This is precisely the point where informational limitations come in. A device equipped with a very large memory and enough speed to go through a very large number of operations within the time available, could afford to base its decisions on a very large amount of data. Man is no such device. He may base a decision on consideration of enormous amounts of data, but he can not do so in a single act. In each single decision process, there must be one instant when all the input data, all the rules applied, and all outputs under consideration are present simultaneously in such a fashion that they are available to conscious information processing. We have made no special studies on the informational limitations of complex decision processes. We may assume, however, that the types of informational limitations which have been found in simpler processes will also occur in more complex processes. If so, then a single decision can take into account only a limited number of elements (logons); the amount of information in each element will be limited (span of absolute judgment); the total amount of information in all logons will be limited (channel capacity); and the time will have both a lower and an upper limit, the latter imposed by forgetting. Furthermore, it seems safe to assume that the Simple Challenge Effect applies; that is, if a decision involves very few elements, then the amount of information for these elements can be greater than if there are many elements involved. Also, and this is very important, it seems to be certain that the Confusion Effect applies, that is, if the informational content of a decision processes becomes very much higher than capacity, confusion results and the final selection is made randomly, and is not coherent with the situation.

We have summarized our investigations on the informational limitations of a unit perceptual process by the crude picture of a daisy (Fig. 2). It is thought of as a storage device; the number of petals represents the limitation on logon content, the size of the petals and the heart, the limitations on information content of the components, and the over-all area, the channel capacity. The decision process, too, depends on the concrescence into a unit of information concerning inputs, outputs, and rules. This unit - be it ever so fleeting - must be stored somehow. The storage device can be symbolically represented by a "decisional daisy", probably similar to the "perceptual daisy" although it might be more complex.

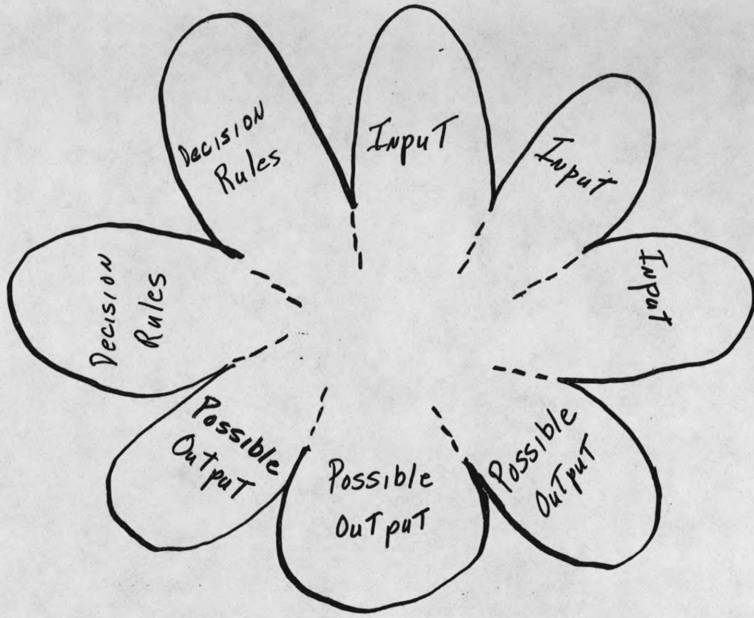

Fig. 2 Symbolic Representation of a Unit Decision Process

The informational limitations are a very good reason why we must make intermediate decisions. If decisions are postponed until the input information gathered surpasses the informational capacity of a unit decision process, then confusion will result, a random selection will be made and much input information will be lost. In this sense, the evaluation officer in our example performs a service to the system even if he is wrong. His statement "targets nos. 5 and 17 are the most immediate threats" may be mistaken, it may kill off valuable information; but, it converts a mass of information which is so large that it is certainly useless into a piece of information of manageable size which <u>may</u> be useful.

We have derived two contradictory postulates: the number of decision centers or decision processes in a complex system should be small so as not to lose input information and waste information capacity, and it should be large in order to avoid the confusion effect. The design of a complex system will involve a compromise between these two postulates. However, knowledge available at this time is not sufficient to pinpoint optimum designs; we cannot do more than point out a principle.

We started out with the statement that each decision process has a motivational and an informational aspect. The motivational aspect is treated by most present studies of decision making, including the applications of game theory. These studies have been very successful in some ways, and not very successfully in others. The application of information theory allows one to make use of an entirely different aspect of decision-making, and it is suggested that this application might lead to important results in the science of organization and management.